

Integrated assessment of combined cooling heating and power systems under different design and management options for residential buildings in Shanghai

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ABSTRACT

As a well-known technique for rational use of energy, the combined cooling, heating and power (CCHP) system is paid more and more attention in building energy conservation activities. In this paper, the performances of typical CCHP systems are investigated for a high-rise residential building, which is experiencing rapid expansion in China. Based on the building's energy consumption, four types of CCHP technologies have been assumed following three design and management modes, namely, heat tracking mode, electricity tracking mode and energy island mode. In order to have a comprehensive understanding of the performance of the assumed CCHP systems, besides the separated energy, economic and environmental assessments, an integrated assessment framework is proposed. According to the simulation results, gas engine and fuel cell based CCHP systems are feasible options from the energy and environmental viewpoints, but at the cost of poor economic performance. From an integrated viewpoint, the gas engine system is the most attractive option if economic performance is taken into account; otherwise the fuel cell system is the best choice. In addition, the selection of proper design and management mode is of vital importance for the adoption of the CCHP system.

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1. Introduction

In recent years, distributed energy resource (DER) has been receiving increasing attention as a good option for future energy systems with respect to sustainable development and low-carbon society development [e.g. [1,2]]. Usually, DER means small scale electric generation units located at or near the end-users, and can be divided into two major sections from the technical points of view. The first section is on-site renewable energy sources, including photovoltaic, biomass energy, small-scale wind and water turbine generators, and so on. The second major area of DER is the combined cooling, heating and power (CCHP) systems using prime mover technologies including gas engines, micro-turbines, steam turbines, Stirling engines and fuel cells [3]. From the long-term viewpoint, the utilization of renewable energy should be a final solution for sustainable development and low-carbon society. However, most of the current renewable energy technologies, e.g. solar, wind energy, etc., have low energy utilization efficiency

and high expense, and thus cannot compete with conventional fossil fuels with respect to the economic performance. On the other hand, from the short-term viewpoint, as an efficient approach to generate electrical and thermal energy from a single fuel source, the CCHP plant is considered to be one of the feasible and effective solutions. The CCHP system recovers the waste heat from the electricity generating process that would otherwise be discarded into the environment. The heat recovered is used to satisfy the thermal demand (cooling, heating, or hot water needs) of an end-user. By recycling the waste heat, the CCHP system can achieve a primary energy efficiency of 60–90%, a dramatic improvement over the average 35% efficiency of conventional fossil fuel based power plants. Higher efficiencies can also contribute to the reduction of air emissions including SO₂ which is the main component of local air pollutions, and CO₂ which is the main threat to the global environment.

Since its first emergence, the CCHP system has spread with varying success to many developed countries, and has played an important role in promoting energy efficiency in these countries. For example, in Japan, the CCHP system has been developed rapidly during the last 20 years. The total generation capacity had increased from 200 kW in 1986 to 9440 MW as of March 2010. The annual capacity of CCHP installed is increasing by a constant 350–400 MW every year since 1986 [4]. In addition, the overall electricity

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capacity of CCHP in the US reached 85 GW in 2011. Among those, there were 2016 commercial CCHP applications with 10,200 MW and 1584 industrial CCHP units with 74,800 MW [5]. On the other hand, as the world's largest energy consumer and CO₂ emitter, China is still in its nascent stage in the introduction of the CCHP system. Currently, the capacity of CCHP applications in China is less than 1000 MW. In the past decades, with the rapid increase in coal consumption, extensive emissions of local air pollutants, including sulfur dioxide (SO₂), nitrous oxide (NO_x), and particulate matter (PM), were released. To overcome the increasingly serious energy and environmental problems (both local and global ones) as well as severe electricity shortage in many cities, the Chinese government has recognized the merits of the high-efficient CCHP system and expected it to play the main role in optimizing energy structure, shaving peak power consumption, increasing energy efficiency, and protecting environment. In 2010, National Energy Administration (NEA) issued "Guiding Opinions for the Development of Natural Gas fueled Distributed Generation". According to the opinions, China will construct 1000 CCHP units in 2011, and decides to expand the CCHP system to all main cities with a total capacity of about 50 GW by the year 2020. Therefore, it is expected that the CCHP system will experience continuing rapid expansion in China in the coming years.

In order to understand the feasible benefits of the CCHP system to promote its penetration in China, the rational design and evaluation from an integrated viewpoint is of vital importance for different end-users with specific prospects. Many studies have been reported on this topic. Hao et al. [6] discussed the role of building cooling, heating and power (BCHP) system in energy and environmental sustainable development as well as its prospects in China, from a macro viewpoint. Wang et al. [7–10] discussed the energy and environmental performances of the CCHP systems for various types of public buildings located in different climate zones in China. Ren et al. [11] examined the feasibility of introducing DER in urban areas of China and found that the CCHP system was the most feasible alternative from a cost-beneficial viewpoint. Cao and Liu [12] simulated the performance of a CCHP system in the air-conditioning season in China, by using thermodynamic and thermoeconomic analyses. However, all above studies focused on the assessment of CCHP systems in public buildings such as hotels, offices, hospitals and schools. As the main component of the building sector in China, residential buildings consumed 319 million tons of standard coal in 2010 which ranked second after the industry sector, although its energy intensity was relatively lower than the public buildings [13,14]. Therefore, it is of vital importance to examine the energy conservation measures, such as CCHP adoption in residential buildings, which is paid little attention in previous studies. On the other hand, the occupancy rate of a residential building is relatively low in the morning and afternoon with a rise at noon, which is quite different from the occupancy pattern of the public buildings (e.g. office) [15,16]. Consequently, the energy consumption in a residential building usually illustrates more fluctuations than that in a public building, which may result in more complicated running schedules of the CCHP system. Based on the above consideration, an integrated assessment of the energy, economic and environmental performances for the CCHP systems accounting for different design and management options and various types of prime movers is necessary.

The purpose of this study is to analyze the energy, economic and environmental performances of residential CCHP systems in China, while considering the influence of the technical type and the design and management strategy. In detail, the paper is structured as follows. Section two presents the assumed technical types, design and management options of the CCHP system, as well as the evaluation methods. In the third section, the numerical application analysis of a high-rise residential building in Shanghai,

China is illustrated. Finally, section four draws a conclusion for the study.

2. Methodologies

While introducing a CCHP system, it is always a wise practice to take into account of various technical options, design and management modes, as well as corresponding energy, economic and environmental performances. The following discussion starts with technical analysis of the CCHP system in order to determine the technical type matching the special needs of the examined application with a number of technically suitable and available prime movers, which is then followed by determination of the feasible design and management modes. Finally, for each CCHP system considered, the economic and social benefits are assessed (see Fig. 1).

2.1. Description of the CCHP system

In order to execute a comparative study, a conventional system has been assumed as a baseline. The energy flows of the conventional system and the CCHP system are illustrated in Fig. 2. The left side is the conventional system and the right side is the CCHP system. Four kinds of energy demands, namely, direct electrical consumption for lights and equipments, heating and cooling demands, as well as hot water load have been considered.

In the conventional system, local utility grid serves all electrical demand which is employed for not only direct power consumption, but also space heating and cooling loads through the operation of room air conditioners. Hot water load is satisfied by a gas boiler fueled by natural gas.

As to the CCHP system, local power consumption could come from either the utility grid, or the on-site generators, or a combination of both. The high-temperature exhaust gas from the CCHP units is recovered to meet the cooling and heating loads through the absorption chiller and heat recovery boiler, respectively. When the recovered heat is not enough, the absorption unit and heat recovery boiler can also be fired by the natural gas directly. On the contrary, if the recovered thermal energy exceeds local requirements, the surplus energy is exhausted directly into the atmosphere. Similarly, according to current electrical standard in China, the excess

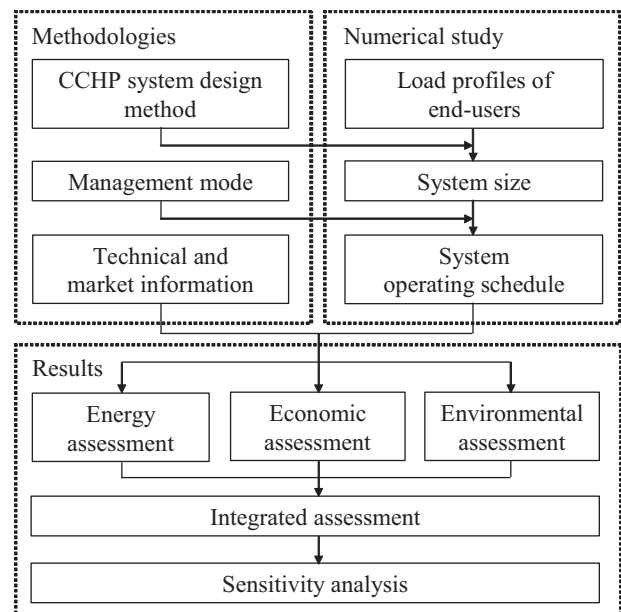


Fig. 1. Flow chart of the analytical procedure.

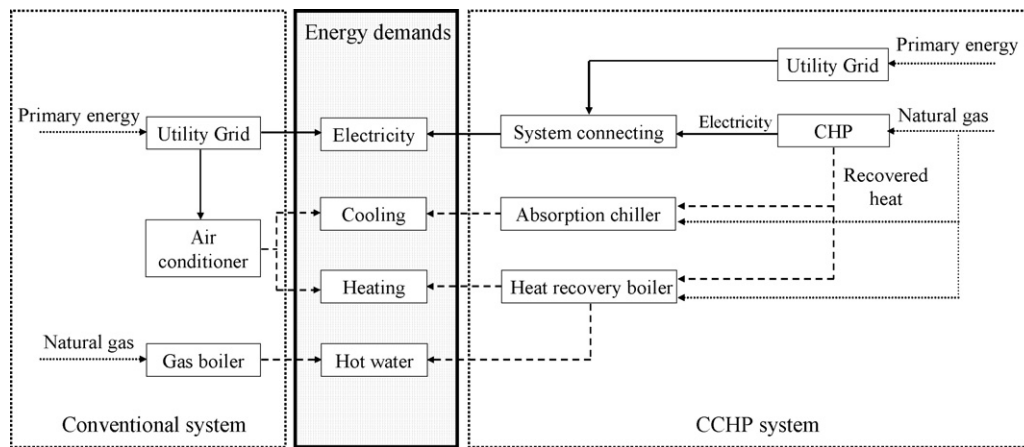


Fig. 2. Super structure of the conventional system and the CCHP system.

electricity out of the CCHP system is not allowed to be sold back to the grid.

As CCHP systems are nowadays well known and widely spread, the main issue is to identify those that will be proven to be more effective and reliable in the long term. With such a variety of proposed measures, the decision maker has to compensate energy, economic, and environmental factors in order to reach the best possible solution that will ensure the optimal selection of the CCHP system for a customer satisfying at the same time the final energy demands and some economic and environmental constraints. Currently, the CCHP technologies which are feasible for small-scale applications include gas turbine (GT), gas engine (GE), Stirling engine (SE) and fuel cell (FC) [17]. Details are illustrated as follows.

2.1.1. Gas turbine based CCHP system

As an established technology available in size ranging from several hundred kilowatts to over several hundred megawatts, gas turbine based CCHP system is a preferred choice for many industrial and commercial applications. Furthermore, in recent years, to serve the small-scale customers, micro-turbines are developed with the size ranging from 30 to 400 kW.

2.1.2. Gas engine based CCHP system

In this system, gas engine is employed as the prime mover. As a widespread and well-known technology, gas engine is attractive for various scale CCHP systems due to its low first cost, fast start-up, proven reliability, excellent load-following characteristics, and significant heat recovery potential.

2.1.3. Stirling engine based CCHP system

As an external combustion engine, Stirling engine is currently exciting interest as the core component of small-scale CCHP units due to its better safety record and high heat recovery efficiency. However, because of its relatively low power generation efficiency, the application of Stirling engine based CCHP system is still at a nascent stage.

2.1.4. Fuel cell based CCHP system

As a brand new technology producing power electrochemically from hydrogen, fuel cell is currently in the early stages of development for on-site application, although it is already being manufactured in a large scale in the automobile industry. There are several different liquid and solid media that support the electrochemical reactions. Among those, phosphoric acid fuel cell (PAFC) is the most widely deployed fuel cell in commercial service.

The main technical and financial specifications of above four prime movers are given in Table 1 [18–23]. In this following analysis, all CCHP units are assumed to be fueled by natural gas.

2.2. Design and management options of the CCHP system

According to the preference of the decision maker, as well as the demand features of the end-users, the CCHP system designer may design its optimal size and employ various operating strategies which can be described as overriding management philosophies used to determine the manner in which a CCHP facility operates. In the following, three typical design and management options are discussed in a detailed way.

2.2.1. Heat tracking (HT) mode

Heat tracking means that the priority is put on the heat production. It is assumed that all thermal energy produced from the CCHP system is consumed by the loads. In this mode, the associated electricity produced by the CCHP system will follow the variation of the produced thermal energy (as determined by the heat-to-power ratio of the selected unit). If the CCHP unit will produce excess electric energy above that is required by the local loads, as is mentioned above, it is not allowed to be sold back to the electric utility for an income.

In order to execute the HT mode, the system size should be determined firstly. Many studies have been reported on the optimization methods for the size design of the CCHP system [24–27]. Different from those difficult optimization models, a common practice called maximum rectangle method, which the capacity of a CCHP is based on the maximum amount of energy annually supplied at full load, may be simply implemented in the load duration curve. The idea of this method is based on sizing the CCHP unit to cover an average instead maximal heat demand while the back-up boiler can meet the peak demand. In other words, it is a size design method based on the concept of maximizing heat amount supplied at full load [28–30]. It can be simply determined based on finding the 'maximum rectangle', where the 8760 hourly heat demand values are sorted in descending order and placed in a load duration diagram. The method prevents dramatic undersize or oversize of the CCHP unit, providing a good compromise between the requirements for a good part of the annual energy demand from the CCHP system and for a sufficient annual operation at high load levels. In addition, in order to keep the power generation unit to run at relatively high output level, the following equation is designed

Table 1
Technical and financial specifications of various CCHP devices.

Item	GT ^a	GE ^b	SE ^c	FC ^d
Electrical efficiency (%)	26	34	12	42
Total efficiency (%)	76	84	72	92
Life time (years)	20	20	20	20
Fuel	Natural gas, biogas, alcohols	Natural gas, biogas	Natural gas, biogas	Hydrogen, natural gas
Capital cost (US\$/kW)	1820	2273	2483	6364
Fixed O&M cost (US\$/kW)	19.50	18.93	21.62	9.69
Variable O&M cost (US\$/kWh)	0.015	0.018	0.020	0.029

^a Sources: The values of efficiencies and capital cost are from [20]; the values of O&M costs are from [21].

^b Sources: The values of efficiencies are from [22]; the values of capital cost is from [20]; the value of O&M costs are from [21].

^c Sources: The values of efficiencies are from [18,19]; the values of capital cost and O&M costs are from [18].

^d Sources: The values of efficiencies are from [23]; the values of capital cost is from [20]; the value of O&M costs are from [21].

to determine the on-off and operating level of the CCHP system [31]:

$$\begin{cases} Q_{\text{power}}^{\text{CCHP}} = 0 & \forall 0 \leq f_{\text{heat}} < \theta \\ Q_{\text{power}}^{\text{CCHP}} = \frac{Q_{\text{heat}}^{\text{LOAD}}}{\delta} & \forall \theta \leq f_{\text{heat}} \leq 1 \\ Q_{\text{power}}^{\text{CCHP}} = R_{\text{cap}}^{\text{CCHP}} & \forall 1 < f_{\text{heat}} \end{cases} \quad (1)$$

where $Q_{\text{power}}^{\text{CCHP}}$ and $R_{\text{cap}}^{\text{CCHP}}$ denote the power generation and rated capacity of the CCHP system, respectively. $Q_{\text{heat}}^{\text{LOAD}}$ is the heating load of the building. f_{heat} indicates the instantaneous fraction of the CCHP system for heat generation. δ denotes the heat-to-power ratio of the CCHP system. θ is the critical fraction determining the on-off status of the CCHP system.

The instantaneous fraction of the CCHP system for heat generation is the ratio of heat load and its potential output if it had operated at full nameplate capacity over a period of time. It can be calculated by the following equation:

$$f_{\text{heat}} = \frac{Q_{\text{heat}}^{\text{LOAD}}}{R_{\text{cap}}^{\text{CCHP}} \cdot \delta} \quad (2)$$

2.2.2. Electricity tracking (ET) mode

In this choice, electricity production is paid the main attention. The CCHP system is operated following the fluctuating electricity load, while the thermal energy produced is fluctuating based on the level of electric energy produced (as determined by the heat-to-power ratio of the selected unit). Therefore, there would be no excess electricity in this operating mode while the surplus heat may be lost to the environment. Similar to the HT mode, the capacities of CCHP systems are decided according to the power duration curve. In addition, the operating level of the CCHP system is determined according to the following equation:

$$\begin{cases} Q_{\text{power}}^{\text{CCHP}} = 0 & \forall 0 \leq f_{\text{power}} < \theta \\ Q_{\text{power}}^{\text{CCHP}} = Q_{\text{power}}^{\text{LOAD}} & \forall \theta \leq f_{\text{power}} \leq 1 \\ Q_{\text{power}}^{\text{CCHP}} = R_{\text{cap}}^{\text{CCHP}} & \forall 1 < f_{\text{power}} \end{cases} \quad (3)$$

where $Q_{\text{power}}^{\text{LOAD}}$ is the electricity load of the building. f_{power} indicates the instantaneous fraction of the CCHP system for power generation.

Similarly, the instantaneous fraction of the CCHP system for power generation is the ratio of electricity load and its potential output if it had operated at full nameplate capacity over a period of time. It can be calculated by the following equation:

$$f_{\text{power}} = \frac{Q_{\text{power}}^{\text{LOAD}}}{R_{\text{cap}}^{\text{CCHP}}} \quad (4)$$

2.2.3. Energy island (EI) mode

This design and management mode means an isolated energy system, which serves all types of energy demands through on-site

generation. It is a promising option for electrifying remote locations where grid extension is not feasible or economical. In this case, the CCHP facility has to be dimensioned to cover the maximum electricity; while, the operation of the CCHP system will follow the fluctuation of real-time electricity load. Therefore, it can also be considered as a special ET mode, the only difference is the larger system size. Details of the running strategies are shown in Eq. (5).

$$Q_{\text{power}}^{\text{CCHP}} = Q_{\text{power}}^{\text{LOAD}} \quad (5)$$

2.3. Assessment criteria

2.3.1. Assessment criteria of energy performance

The CCHP system exploitation provides higher utilization of input fuel, thus, energy performance assessment is one of the most important evaluation indexes for the CCHP system. Generally, it can be executed by the calculation of the primary energy saving ratio (PESR) which is defined as the rate of the energy savings of the CCHP system (the difference between primary energy input in the conventional energy system and the CCHP system) to the primary energy consumption of the conventional energy system. It is the key factor determining the energy performance of the CCHP system, and can be expressed as follows:

$$\text{PESR} = \frac{Q_{\text{input}}^{\text{CONV}} - Q_{\text{input}}^{\text{CCHP}}}{Q_{\text{input}}^{\text{CONV}}} \times 100\% \quad (6)$$

where $Q_{\text{input}}^{\text{CONV}}$ and $Q_{\text{input}}^{\text{CCHP}}$ denote the primary energy input in the conventional energy system and the CCHP system, respectively.

Total annual primary energy consumption of the conventional energy system is composed of the power consumption for electricity, heating and cooling loads, as well as natural gas consumption for hot water demand, as shown in Eq. (7).

$$Q_{\text{input}}^{\text{CONV}} = \frac{Q_{\text{power}}^{\text{LOAD}}}{\eta_{\text{grid}}} + \frac{Q_{\text{heating}}^{\text{LOAD}}}{\text{COP}_{\text{heating}}^{\text{HP}} \cdot \eta_{\text{grid}}} + \frac{Q_{\text{cooling}}^{\text{LOAD}}}{\text{COP}_{\text{cooling}}^{\text{HP}} \cdot \eta_{\text{grid}}} + \frac{Q_{\text{water}}^{\text{LOAD}}}{\eta_{\text{boiler}}} \quad (7)$$

where $Q_{\text{heating}}^{\text{LOAD}}$, $Q_{\text{cooling}}^{\text{LOAD}}$ and $Q_{\text{water}}^{\text{LOAD}}$ denote the space heating load, space cooling load and hot water load, respectively. $\text{COP}_{\text{heating}}^{\text{HP}}$ and $\text{COP}_{\text{cooling}}^{\text{HP}}$ are the coefficients of performance (COP) of the heat pump for heating and cooling, respectively. η_{grid} and η_{boiler} indicate the efficiencies of the utility grid and the boiler, respectively.

On the other hand, total annual primary energy consumption of the CCHP system includes the energy consumption for utility electricity, on-site power generation, as well as direct fuel combustion for absorption chiller and heat recovery boiler, as illustrated in Eq. (8).

$$Q_{\text{input}}^{\text{CCHP}} = \frac{Q_{\text{power}}^{\text{GRID}}}{\eta_{\text{grid}}} + \frac{Q_{\text{power}}^{\text{CCHP}}}{\alpha} + \frac{Q_{\text{cooling}}^{\text{AC}}}{\text{COP}_{\text{direct}}^{\text{AC}}} + \frac{Q_{\text{heating}}^{\text{RB}}}{\eta_{\text{boiler}}} \quad (8)$$

where $Q_{\text{power}}^{\text{GRID}}$ is the power purchase from the utility grid. $Q_{\text{cooling}}^{\text{AC}}$ and $Q_{\text{heating}}^{\text{RB}}$ are the cooling load satisfied by direct gas consumption

for absorption chiller and the heating load satisfied by the heat recovery boiler, respectively. COP_{direct}^{AC} denotes the COP of the absorption chiller. α indicates the electricity efficiency of the CCHP system.

2.3.2. Assessment criteria of economic performance

Economic performance is one of the most cited reasons of introducing the CCHP system. Generally, there are two ways for the assessment of the economic performance of the CCHP system: static analysis and dynamic analysis. The former one is a simple economic analysis method, which does not consider the time value of the money and the lifetime of the equipments. On the contrary, the latter one pays enough attention to the time value of the money which is indicated by the discount rate.

As is known to all, a CCHP system usually has higher initial investment and lower running cost compared with the conventional energy supply system. In order to assess the economic performance of the CCHP system in an integrated way, the net present value (NPV) which is a widely accepted dynamic analysis method, is employed in this study.

NPV is defined as the sum of the present values of the individual cash flows in both incoming and outgoing. It can be calculated by the following equation:

$$NPV = \sum_{t=0}^{LIFE} \frac{(CI_t - CO_t)}{(1 + DR)^t} \quad (9)$$

where CI_t and CO_t denote the incoming and outgoing cash flow in year t . DR is the discount rate. $LIFE$ indicates the life time of the CCHP system.

In this study, the outgoing cash flow mainly includes the investment cost for the CCHP units, and the running cost (fuel cost, operation and management cost, possible taxes, etc.), as shown in Eq. (10).

$$CO_t = IC_t + RC_t \quad (10)$$

where IC_t and RC_t are the annualized investment cost and running cost of the CCHP system, respectively.

The annual benefits of the CCHP installation comes mainly from: the substitution for the purchased electricity with the electricity produced by the CCHP system, and the substitution for the purchased or conventionally produced thermal energy with the thermal energy being produced by the CCHP system. Therefore, the incoming cash flow can be described as annual energy cost savings compared with the conventional system, as shown in Eq. (11).

$$CI_t = FC_t^{CONV} - FC_t^{CCHP} \quad (11)$$

where FC_t^{CONV} and FC_t^{CCHP} are the energy costs of the conventional energy system and the CCHP system, respectively.

2.3.3. Assessment criteria of environmental performance

Considerable environmental benefit is another incentive for the introduction of the CCHP system. In this study, the environmental performance is assessed using the CO_2 emissions reduction ratio (CERR) which is defined as the ratio of the reduced CO_2 emissions (the difference between CO_2 emissions in the conventional system and the CCHP system) and the CO_2 emissions in the conventional system, as shown in Eq. (12).

$$CERR = \frac{E_{CO_2}^{CONV} - E_{CO_2}^{CCHP}}{E_{CO_2}^{CONV}} \times 100\% \quad (12)$$

where $E_{CO_2}^{CONV}$ and $E_{CO_2}^{CCHP}$ denote annual CO_2 emissions of the conventional energy system and the CCHP system, respectively.

CO_2 emissions from the conventional system included the CO_2 emissions from the natural gas and grid electricity for both

electricity and heat consumption, and they can be calculated according to Eq. (13). Similarly, annual CO_2 emissions from the CCHP system are composed of the emissions of grid electricity, natural gas consumption for CCHP operation and direct combustion, as shown in Eq. (14).

$$E_{CO_2}^{CONV} = \left(Q_{power}^{LOAD} + \frac{Q_{heating}^{LOAD}}{COP_{heating}^{HP}} + \frac{Q_{cooling}^{LOAD}}{COP_{cooling}^{HP}} \right) \cdot CC_{power} + \frac{Q_{water}^{LOAD}}{\eta_{boiler}} \cdot CC_{gas} \quad (13)$$

$$E_{CO_2}^{CCHP} = Q_{power}^{GRID} \cdot CC_{power} + \left(\frac{Q_{power}^{CCHP}}{\alpha} + \frac{Q_{cooling}^{AC}}{COP_{direct}^{AC}} + \frac{Q_{heating}^{RB}}{\eta_{boiler}} \right) \cdot CC_{gas} \quad (14)$$

where CC_{power} and CC_{gas} are the carbon contents of the grid electricity and the natural gas, respectively.

2.3.4. Integrated assessment

A well designed CCHP system should balance economical saving, real energy savings, and net emission of pollutants. In the sustainability assessment of the CCHP system, it is often necessary to take into account all above aspects of sustainability at the same time. However, the above criteria are usually contradictory objectives; for example, it is often expensive to utilize environmentally friendly systems. Therefore, in order to achieve a system determination that would be the most appropriate CCHP system with the most suitable operation mode for particular buildings, an integrated assessment is necessary.

Because the energy, economic and environmental criteria are generally different aspects and cannot be integrated directly, all specific criteria should be normalized so as to make them comparable. In this study, because the preferabilities for all three criteria increase with increase of the argument, an increasing normalization function is determined by the following equation:

$$NI_{i,j} = \begin{cases} 0 & \text{if } x_{i,j} \leq MIN_j \\ \frac{x_{i,j} - MIN_j}{MAX_j - MIN_j} & \text{if } MIN_j < x_{i,j} \leq MAX_j \\ 1 & \text{if } x_{i,j} > MAX_j \end{cases} \quad (15)$$

where $NI_{i,j}$ is the normalized indicator of the i th system option and j th assessment criterion. $x_{i,j}$ is the real value of the assessment criterion for each system option. MIN_j and MAX_j are the minimum and maximum values of each assessment criterion, respectively.

The second step in this procedure is the definition of the synthesizing function, which will represent the general index. The general index method comprises the formation of an aggregative function with the weighted arithmetic mean as the synthesizing function shown in the following equation:

$$GI = \sum_j^m w_j NI_{i,j} \quad (16)$$

where GI denotes the general index. w_j is the weight coefficient of the assessment criteria. m indicates the number of assessment criteria.

The weight coefficient vector is usually determined according to the preference of specific decision maker. In addition, as shown in the following equation, the sum of all the weight coefficients should be equal to 1.

$$w_1 + w_2 + \dots + w_m = 1 \quad (17)$$

3. Numerical study

To analyze the application performances of the CCHP systems for residential buildings, a numerical study is presented below. Different CCHP solutions are evaluated and compared by using the proposed general and systematic procedure described in Section 2. In particular, different prime movers and design and management

modes are considered, to highlight the impact of different technical and management options on the CCHP system performances.

3.1. Building description and energy demands

The site studied in this paper is a typical high-rise residential building located on Fuxing Road, Shanghai, which is a city with a typical subtropical maritime monsoon climate. Annual average temperature is about 16 °C. The hottest month occurs generally in July with a monthly average temperature of about 28 °C and the coldest month is in January, with a monthly average temperature of about 4 °C. The examined building is an 11-floor reinforced concrete (RC) building built in the 1980s, with a total floor area of about 5609 m² and a height of about 30.8 m. Due to the improvement of living standard, energy consumption has been experiencing continuing rise, which leads to serious power shortage in these residential buildings. On the other hand, it may take a long period to construct a centralized power plant and is expensive to expand the electricity transmission system. Therefore, in this study, as an alternative consideration, a CCHP system is examined to solve the problem of power shortage in the high-rise residential building, from energy, economic and environmental points of view.

For any CCHP system under investigation, detailed knowledge about energy end-use loads is of vital importance for selecting the appropriate system components and corresponding operating strategies. Generally, energy consumption in buildings can be obtained through direct on-site measurement or simulation with some building energy simulation software, for example, Energy-Plus, Flexsim, TRNSYS, DOE-2, and so on. In this study, the electrical demand is calculated by multiplying the energy consumption units of various electric appliances and their operating hours while considering the hourly running schedules and the simultaneity coefficients [32]. It should be indicated that because the space heating and cooling loads are assumed to be satisfied by the absorption chiller and heat recovery boiler (see Fig. 2), they have been excluded from the conventional electricity consumption with heat pump application. On the other hand, the thermal demands are calculated by using the simulation software DeST (Designer's Simulation Toolkit), which is an annual building energy consumption analysis software doing simulation hourly. By inputting local weather data, building construction, building materials and envelope components, zoning and system type, operating schedules and other information, the software tool can report annual dynamic thermal load while taking into consideration the coupling between building and system [33]. In this study, the examined building has a reinforced concrete structure with brick walls and single-layer glass for windows. Some other parameter including the temperature and humidity setting points, fresh air requirements, heat dissipations, etc. are assumed to have the default values.

Fig. 3 shows the load demand duration curve, which reveals the characteristics of building's energy consumption. It illustrates the peak load demand and each demand level range with annual number of hours, which is important information in deciding CCHP capacity. As to the EI mode, the capacity of the prime mover can be easily determined as the peak electrical load (145 kW). On the other hand, as to the HT and ET modes, as mentioned in Section 2, the simple method based on the load duration curve is employed to choose the prime mover size. In the HT mode, the capacity is determined based on the thermal duration curve. As shown in Fig. 3, based on maximizing the area below heat duration curve, the maximum heat (73 kW) from the power generation unit, and the duration time (3121 h) are determined. Similarly, the maximum electricity (44 kW) of the power generation unit in ET mode can be determined according to the electricity duration curve.

In addition, heat-to-power ratio is another key factor influencing the effective operation and corresponding energy, economic

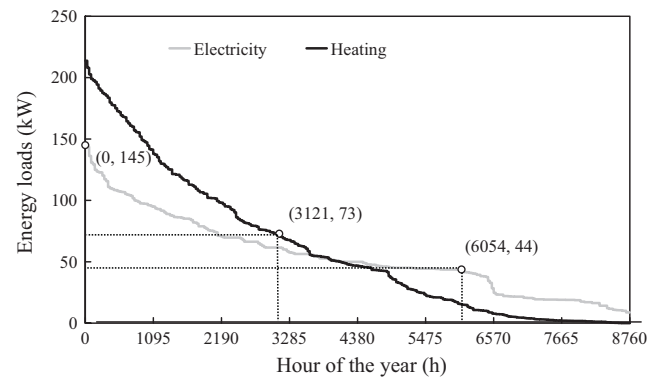


Fig. 3. Load demand duration curves for the residential building.

Table 2

Technical and market information for analysis.

Item	Variable	Mean value
Grid electricity	Efficiency (%)	35
	CO ₂ intensity (kg/kWh)	0.88
	Tariff rate (\$/kWh)	0.10
Natural gas	CO ₂ intensity (kg/kWh)	0.22
	Price (\$/kWh)	0.03
Absorption chiller	COP	0.7
Boiler	Efficiency (%)	80

and environmental performances of the CCHP system. Fig. 4 illustrates the duration curve of heat-to-power ratio for the studied residential building, with a range of [0, 7.3] throughout the whole year. The heat-to-power ratios of the examined four types of prime movers are also indicated in the figure, with a ranking order of SE > GT > GE > FC. According to a previous study, the CCHP system will achieve the maximum energy saving ratio when the heat-to-power ratio of the user is equal to the technology-specific ratio of the prime mover. The more close the heat-to-power ratio of the user is to that of the prime mover, the better energy performance will be [20]. Therefore, due to the relative high heat-to-power ratio, it will be difficult for the SE based CCHP system to match the thermal and electrical demands of the building. Detailed discussion will be illustrated in the next section.

In addition, to evaluate the energy, economic and environmental performance of the CCHP system, some main assumed data are summarized in Table 2 [25,34,35].

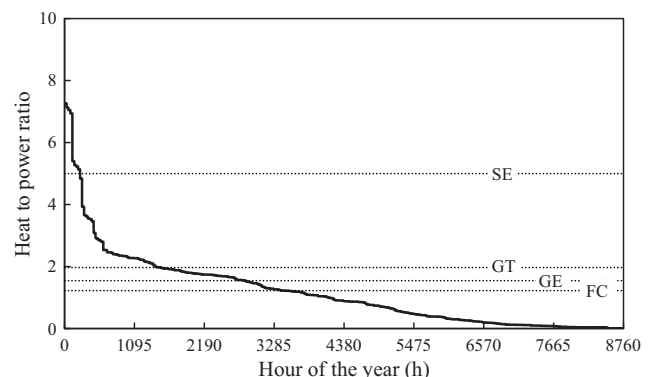


Fig. 4. Duration curve of heat-to-power ratio for the residential building.

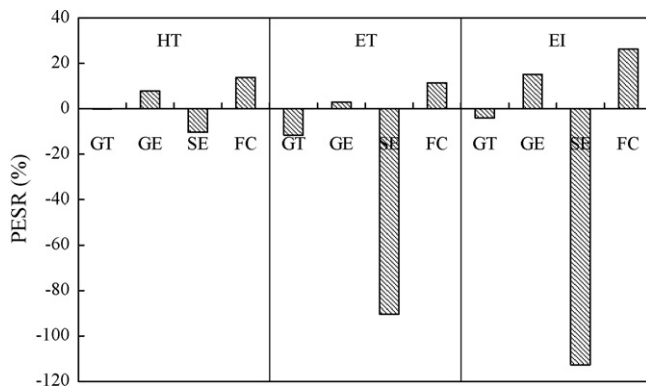


Fig. 5. Primary energy saving ratio for various options.

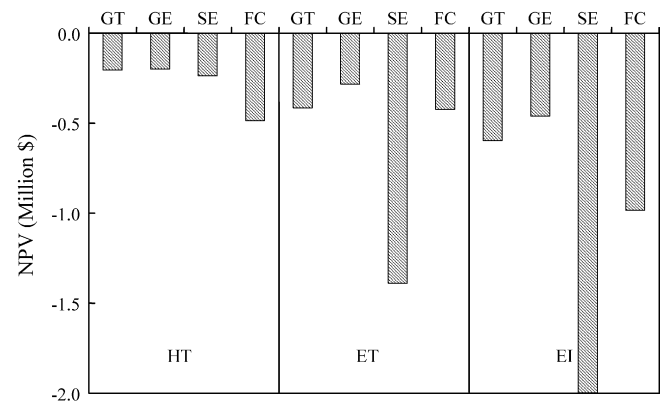


Fig. 6. Net present value for various options.

3.2. Results and discussion

3.2.1. Assessment of energy performance

An important and indisputable aspect of a CCHP system implementation is its potential energy saving benefits. In this study, the primary energy saving ratios for various options with different prime movers and design and management modes are calculated and illustrated in Fig. 5. Unexpectedly, six options of all examined twelve alternatives result in negative PESR. Especially, the SE system at EI mode achieves a relatively low PESR which is lower than -110% . In other words, this option will consume more than twice as much primary energy as the conventional system. In addition, the GT system also encounters minus values of PESR for all design and management modes, although the situation is better than that of the SE system. This is mainly because of their relatively high heat-to-power ratios (see Fig. 4), which deflect the main range in the demand side. From the technical viewpoint, the FC system is recognized to be the most suitable technique for residential application followed by the GE system, with satisfying energy savings. Comparing with other CCHP technologies, the FC system has a higher PESR due to its high power generation efficiency (42%) and moderate heat-to-power ratio.

On the other hand, from the viewpoint of design and management, all examined CCHP systems at HT mode result in higher PESR than that at ET mode. However, the PESR values of the GE and FC systems at HT mode are lower than the values at EI mode, which is considered as a special ET mode. This is because the examined PESR depends on not only the operating mode, but also on the size of the prime mover. By comparing the results at ET and EI modes, the maximum rectangle method used in this study cannot achieve the optimal system size with largest energy saving, nevertheless it may provide a good compromise. Moreover, it is important to note that the EI mode which determines the system size based on the peak electrical load cannot be recognized to be the optimal option, although it may result in better energy performance than the HT and ET modes.

All in all, from the viewpoint of energy performance, GE and FC based CCHP systems are suitable technical options for the residential building examined in the current case study. Among the examined three design and management options, the EI mode achieve the best energy performance, followed by the HT mode and ET mode.

3.2.2. Assessment of economic performance

In order to obtain a complete and accurate picture of the advantages of a CCHP system implementation, its economic performance should be assessed in a quantitative way. The NPVs for various options are calculated and illustrated in Fig. 6. Generally, minus NPVs in the life cycle period are encountered by all CCHP systems

with different design and management modes. It means that it is unfeasible to introduce the CCHP system for the studied residential building from the economic point of view. As to the relative comparison, the GE system enjoys better economic performance than the other three systems under all three design and management options. Although the FC system has relatively high initial cost which is about three times more than other systems, its NPV is larger than that of the SE system at the ET and EI modes. This is mainly due to the poor energy performance of the SE system (see Fig. 5), which results in low or even negative incoming cash flow. On the other hand, the CCHP systems at HT mode may achieve better economic performance than that at ET and EI modes, although they actually result in absolute cost increase.

According to the above discussion, from the economic point of view, the CCHP system cannot be considered as an attractive energy supply system for the residential buildings at current situation. This is mainly due to the oversized CCHP system especially at EI mode (see Fig. 3), the unbalanced heat-to-power ratio between the demand side and the prime movers (see Fig. 4), the relatively high capital cost of the CCHP devices (see Table 1), as well as the relatively low electricity tariff rate comparing with the natural gas price (see Table 2). Among all examined alternatives, the relatively better option is the GE system under HT mode, which needs positive promotion measures for its penetration. However, as is mentioned above, in order to insure the stable electricity supply for the studied residential building, it would be expensive to extend current power and grid infrastructures. If all the opportunity benefits (improvement of the reliability for power supply, avoidance of the extension of the power transmission and distribution system, etc.) of the CCHP system adoption are taken into consideration, the economic performance of the CCHP system will be implicitly improved. However, in this study, the research boundary has been limited to the local energy system which covers four types of final energy consumption forms satisfied by the CCHP system; while the infrastructure of the macro grid and the assessment of the system reliability are paid little attention. In the following study, in order to have a comprehensive understanding of the benefits of the CCHP system, the economic values of the improvement of system reliability and the avoidance of the extension of grid infrastructure are expected to be quantified and integrated into the assessment of the economic performance of the CCHP system.

On the other hand, most of previous studies on the CCHP system adoption in China have focused on the public buildings which is put the priority in the building energy conservation activities. This is because the public buildings usually have larger energy intensity than the residential buildings, and are easier for the execution and management of the energy conservation measures. According to the findings illustrated in Ref. [10], among the examined four

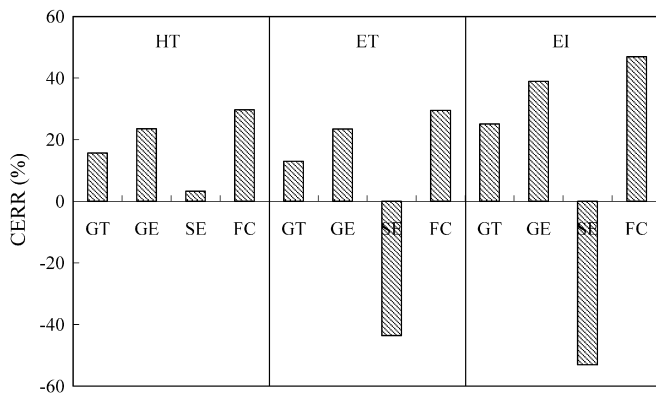


Fig. 7. CO₂ emissions reduction ratio for various options.

types of public buildings located in Shanghai, school resulted in minus annual total cost saving ratio; while hotel, office and hospital enjoyed satisfying economic performance. It is not surprising that the public buildings have better economic performance than the residential building while introducing the CCHP system. This is because on the one hand, the public buildings (e.g. hospital, hotel) usually have relatively larger thermal demands and can utilize the recovered heat from the CCHP system in a better way; on the other hand, a higher electricity tariff rate is set for the public buildings in China and thus makes the CCHP system with less grid electricity consumption be more competitive. Therefore, in order to promote the introduction of CCHP systems in residential buildings in China, besides the continuing technological innovation, the policy reform (e.g., regulation of electricity tariff) is also very important.

3.2.3. Assessment of environmental performance

Environmental impact is an important factor that cannot be neglected in any energy related projects. Fig. 7 shows the CERR values for various options. Generally, the application of the CCHP system in the residential building results in better environmental performance than the energy and economic ones examined in previous sub-sections. Most of the options achieve satisfying CERR; the only exception is the SE system under ET and EI modes. As to the same design and management mode, the FC system enjoys the best environmental performance with a CERR more than 30%, followed by the GE system, GT system and SE system. On the other hand, except the SE system, the EI mode for other three systems results in larger CERR, followed by the HT mode and ET mode.

Therefore, similar to the energy performance, due to the relatively high efficiency (both power generation efficiency and total efficiency), the FC system is considered to be the most suitable technology for the residential CCHP system. Alternatively, the GT system and GE system may be also good options with relatively high CERR more than 10% under all three design and management modes. In addition, although the value of PESR is negative for the SE system under HT mode, its CERR is positive due to the fuel transfer to the natural gas which is considered as a relatively clean fuel.

3.2.4. Integrated assessment of 3E performance

According to the above results, each technology or design and management mode may have its advantages and drawbacks. Some have good energy saving and environmental effect with poor economic performance. Others achieve better economic profitability with lower environmental benefit. Therefore, each of above assessment only considers a particular aspect of the CCHP system, neglecting the others; moreover, they usually lead to different conclusions. In order to achieve a comprehensive determining on the most appropriate CCHP system for the particular building, an integrated assessment is necessary considering energy, economic and

Table 3
Integrated assessment results of various system options.

Design and management mode	Primary mover	Indicators			Overall rating	Priority
		PESR	NPV	CERR		
HT	GT	0.81	1.00	0.69	0.831	7
	GE	0.87	1.00	0.77	0.878	2
	SE	0.74	0.98	0.56	0.760	9
	FC	0.91	0.84	0.83	0.859	4
ET	GT	0.73	0.88	0.66	0.756	10
	GE	0.83	0.95	0.77	0.850	6
	SE	0.16	0.34	0.09	0.198	11
	FC	0.89	0.88	0.83	0.865	3
EI	GT	0.78	0.78	0.78	0.781	8
	GE	0.92	0.85	0.92	0.898	1
	SE	0.00	0.00	0.00	0.000	12
	FC	1.00	0.56	1.00	0.854	5

environmental (3E) aspects. In this study, the integrated assessment method proposed in Section 2 has been employed. While assuming all assessment criteria are given the same priority with the same weight coefficients, Table 3 shows the normalized indicators of the three assessment criteria as well as deduced overall rating and priority. The GE system at EI mode is the best choice with a compromised preference; while the SE system at EI mode is the worst one. Looking into the table, it can be concluded that the GE and FC systems are considered to be more suitable for the residential CCHP system; but the GT and SE systems are not attractive. In addition, different design and management mode may be suitable for different CCHP technology. For example, the GE system receives high priorities at HT and EI modes; while the FC system is the best choice at ET mode.

3.2.5. Sensitivity analysis of natural gas price on the economic performance

According to the above analysis, currently, the introduction of CCHP systems may result in good energy and environmental performances but no economic benefit in the examined residential buildings. In other words, for some of the examined options, the achieved energy saving and emissions reduction are at the cost of increased spending to satisfy the same energy demands. However, the economic performance is considered to play the main role in the final decision making of CCHP system adoption, especially for a residential building. Therefore, in this section, the sensitivity analysis of natural gas price, which is recognized to be one of the main factors determining the economic performance of the CCHP systems, is examined. Actually, as is known to all, the price for natural gas will very probably continue to rise due to the enormous demand from some developing countries (e.g. China) in the following years [36,37]. However, if a reasonable price system and mechanism which can reflect the environmental value and external cost of the fuels, the price of natural gas may become competed with other fossil fuels (e.g. coal). On the other hand, as a market based measure to promote the penetration of gas fired distributed power generating systems, the price discount for natural gas consumption in the CCHP systems has illustrated its success in some developed countries. For example, in Japan, a relatively attractive price which is less than half of general price has been set for the gas consumption in CCHP systems [38].

Based on the above consideration, in this study, while assuming the natural gas price is reduced to as low as half of the current value, the sensitivity of the NPV is examined and compared for various systems under different design and management modes. According to the profiles shown in Fig. 8, along with the further decrease of natural gas price, as is expected, the NPVs increase for all options.

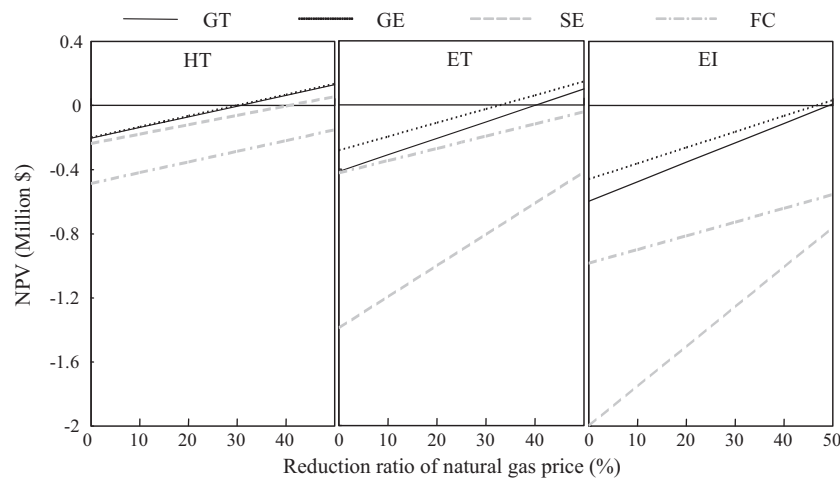


Fig. 8. Influence of natural gas price on NPV for various options.

The NPV of the SE system seems to be more sensitive to the natural gas price than other three systems, especially at the ET and EI modes. In order to make the CCHP system be economically feasible with a positive NPV, the minimum reduction ratios of natural gas price are 31%, 41% and 51% for the GT system at the HT, ET and EI modes, respectively. Similarly, as to the GE system, the values are 30%, 33% and 47% at the HT, ET and EI modes, respectively. However, the FC system cannot receive the economic benefit even the natural gas price is reduced to half of current value at all three design and management modes. Therefore, from the economic point of view, the GE system is the most feasible technical option to be widely introduced with proper promotion measures.

4. Conclusions

In this study, a proposed general and systematic procedure, suitable for the energy, economic, environmental and integrated assessment of the CCHP system installations has been presented and applied successfully to a high-rise residential building while considering various prime movers and design and management modes. According to the analytic results, the following conclusions can be deduced.

- (1) From the energy and environmental viewpoints, GE and FC based CCHP systems are feasible technical options for residential application; while GT and SE systems result in increased energy consumption and CO₂ emissions due to the not well balanced heat-to-power ratio with the demand side.
- (2) From the economic point of view, the CCHP system is not feasible to be introduced in the residential building at current situation.
- (3) From an integrated viewpoint, if the economic performance is paid enough attention, the GE system is the most attractive option; otherwise, the FC system is the best choice.
- (4) Different design and management mode is suitable for different CCHP technology. Under the integrated assessment framework, the GE system is the best choice at HT and EI modes; while the FC system is more attractive at ET mode.
- (5) The reduction of natural gas price is expected to promote the penetration of CCHP system application in residential buildings. The GE system will be economically feasible as the natural gas price is reduced to 70% of current value, following the HT mode.

Of course, the numerical results obtained in the case study cannot be generalized to other CCHP systems. However, the conceptual

exploration of the results has provided a useful indication of the type of CCHP solution relevant to different prime movers and design and management strategies. In the following studies, the assessment procedure presented in this study is expected to be used to other building types located in different regions, so as to examine the feasibility of CCHP system penetration in a more comprehensive way. In addition, because the CCHP system is always introduced under specific macro and micro economic environments, a long-term energy system assessment model which may account for not only the expected increment of energy demands and dynamics of energy prices but also the feasible technical improvements is expected to be developed. In this way, an integrated assessment of the CCHP system can be realized by extending the conventional physical boundary of the energy system to wider economic, social and political boundaries.

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